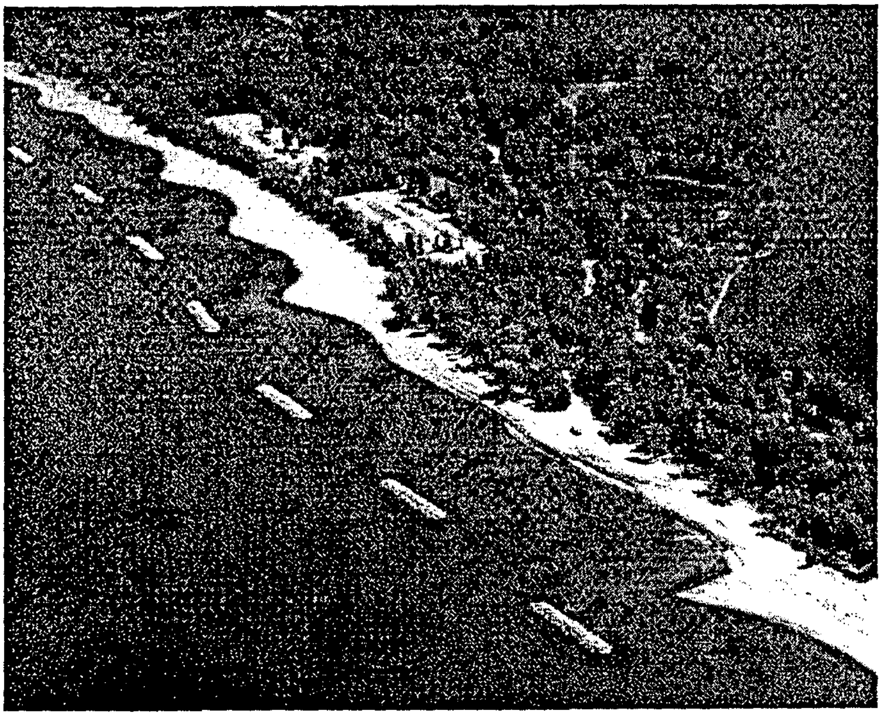
Presque Isle Sediment Transport Study
Part I: Narrative



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Contract Number FDC9301

June 1996

Pennsylvania Coastal Zone Management Program

THE BREAKWATER SEDIMENT TRANSPORT STUDY
JUNE 30, 1996

CZM PROJECT NUMBER 94-PS.10

A REPORT OF THE PENNSYLVANIA DEPARTMENT OF ENVIRONMENTAL PROTECTION TO THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION PURSUANT TO NOAA AWARD NO. NA470Z0248

This project was financed in part through a Federal Coastal Zone Management Grant from the Pennsylvania Department of Environmental Protection, with funds provided by NOAA. The views expressed herein are those of the author(s) and do not necessarily reflect the views of NOAA or any of its subagencies.

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Introduction

From October 1989 to November 1992, the Presque Isle Shoreline Erosion Control Project constructed fifty-five offshore segmented breakwaters with beachfill along the Lake Erie perimeter of the 11 km (7 m) recurved spit which is the location of Presque Isle State Park, Erie, Pennsylvania. Each ca. 45.7 m (150 ft) long breakwater has a crest elevation of 2.4 m (8.0 ft) above Low Water Datum; is offset approximately 61 m (200 ft) from the shoreline; and is separated from adjacent breakwaters by a gap of 106.7 m (350 ft). The world's largest project of its kind, the purpose of the $23.7 million breakwater construction was to generate a more stable shoreline configuration by reducing the wave energy reaching the peninsula's shoreline and by decreasing the rates of sediment transport both offshore and along the shoreline.

As anticipated, although often in unforeseeable ways, the presence of the breakwaters changed the dynamics of how waves and currents affect the shoreline, including the transport of sediment along the peninsula. The primary goal of the present Presque Isle Sediment Transport Study is to clarify the role of the breakwaters in the maintenance of the nearshore zone and adjacent beaches. In particular, the investigation addresses the modifications necessary for shoreline management in order to encompass breakwater-induced changes in the dynamics of the system.

The dynamics considered include the effect of breakwaters on:

(1) patterns of sediment exchange between the nearshore zone and the adjacent beaches;
(2) morphology of the nearshore zone and of the beaches (including beach width);
(3) changes in the morphology of the nearshore and beaches associated with differing wave regimes (including storm events);
(4) changes in the nearshore currents.

Study Areas

Detailed study grids were set up at Beach 6, Lighthouse Beach, and Beach 10 (Appendix A:1). These areas were chosen because each represents an area of concern relative to the management of the Presque Isle beaches and each represents a dynamically distinct area of Presque Isle (Appendix A:2). The detailed study grids that were selected also overlap the detailed monitoring areas annually investigated by the U. S. Army Corps of Engineers and will, thus, serve to augment that ongoing study. The grid systems were tied into the U.S. Army Corps of Engineer's baseline by Pennsylvania State surveyors who established control points of known northings and eastings at each location. They also established front and back guide posts for each transect line to extend out into the nearshore zone at right angles to the shoreline trend. The detailed grid at Beach 6 encompasses Breakwaters 20 through 24; at Lighthouse Beach, Breakwaters 43 through 47; and at Beach 10, Breakwaters 57, 58, and the three prototypes 1, 2, and 3. The first two detailed grids consist of one profile transect running through the center line of five breakwater structures and six profile transects running between the breakwater structures. At Beach 10 the grid consists of eight profile transect lines of which five run through the center lines of the breakwaters and three run between the newly constructed breakwaters.

The management concern for the Beach 6 area is due to the chronic need for beach nourishment both before and after breakwater construction. A clearer understanding of the dynamics in the Beach 6 area will permit optimization of the nourishment program there. In the Lighthouse Beach area, the downdrift portion beyond the lighthouse jetty (to the east) is an area similarly in need of annual replenishment. Again, the understanding of sand transport mechanisms extant in the area is needed to guide the necessary nourishment program. Beach 10 area was chosen partially in response to concern over the possibility that the presence of the breakwaters might result in the starving of the Gull Point region immediately down-drift. Understanding and monitoring the dynamics of the Beach 10 area could provide data regarding such a possibility.

The three areas chosen are dynamically distinct from one another (Appendix A:2). The Beach 6 area represents the neck of the Peninsula which has been known to be dominantly erosional. The Lighthouse Beach segment has been referred to as transitional or a nodal point where erosion-dominance gives way to a rough balance between erosion and deposition. The Gull Point segment, including Beach 10, has been dominantly depositional. The characterization of the areas as described dates from at least 1877 and continued to the time of breakwater construction. A fine-tuning of this characterization presented by Pope and Gorecki in 1982 suggests that the nodal point in the Lighthouse Beach area as determined by early surveys had, by 1982, shifted east along the peninsula and erosion was then dominant all the way to Beach 10 beyond which depositional processes prevailed. Investigation in the three areas was partially designed to determine if the overall situation has changed. If the breakwaters are slowing sediment transport, as hoped, the nodal point may be shifting back to the Lighthouse Beach area.

Because each of the three detailed study areas are in a distinct dynamic regime, the influence of the breakwaters on their dynamics, including sediment transport is, not surprisingly, different at each locality and is discussed separately below.

Conclusions concerning the dynamics of the system at each of the detailed study areas and recommendations for their management are based on a model developed from the integration of the products of various aspects of this study which include:

A. Aerial photographs
B. Shoreline maps
C. Detailed topographic maps of the beach and nearshore
D. Volumetric change maps (cut and fill) showing contoured areas of erosion and deposition
E. Comparison with pre-breakwater nearshore and beach configurations
F. Successive profiles from the exposed beach to seven meters depth for each mapping day
G. Current studies using drogues;
H. Sand transport studies using native fluorescent tracer sand
I. Littoral Environmental Observations (LEOs)
J. Sand Transport Volumes (based on computer analysis of sand volume changes between surfaces)

Recognizing that the results of this study depend on the validity of the generated model, the rationale for conducting each type of investigation accompanied by a brief consideration of the methodology employed is discussed below. The results of the individual investigations are presented as the products listed above and are included in their entirety in the Appendix Volume. Specifics concerning the results are referred to and interpreted in the discussion of each of the three detailed study areas.

Rationale and Methodology

A: Aerial Photographs

Rationale

A small plane was employed to obtain oblique aerial photographs of natural bottom structures built by moving sand on the lake floor in the nearshore zone and beaches through the zebra mussel-clarified waters of Lake Erie. The ability to actually see bottom structures such as bars and troughs is very useful in interpreting maps and profiles which have been essentially generated by remote sensing. In this manner, it is possible to see the bottom surfaces which were obscured from view during mapping by rod surveying and by generating fathometer traces. Via this medium, the "big picture" or context of distribution and relationship of features is obtained and can be used as ground truth to check the accuracy of the instrument-generated lake floor contours. Additionally, aerial photography has the potential to extend the interpretation of lake bottom structures to areas beyond the actual detailed-mapping zones in order to understand how the detailed area fits into the larger system. In other words, features observable outside the study area may provide evidence of conditions updrift and/or downdrift without the expenditure of additional time, effort, and capital.

Method

The procedure involved the renting of a small plane and flying over the areas in times of clear, calm water and with a high sun angle. Photographs in a 35 mm color slide format with a Polaroid filter were taken out of an open window of the plane at an altitude of 90 m to 305 m (300 ft to 1000 ft).

Products

Overflights with photography were conducted on 16 June and 10 August 1995. Aerial photographs in the Appendix include Beach 6 (A:3); Lighthouse Beach (A:34-36); and Beach 10 (A:60).

B. Shoreline Maps

Rationale

Mapping of the shoreline on successive dates permits analysis of beach width changes which, in turn, broadly indicates accretion or erosion. The formation and removal of tombolos is readily visible and the configuration of the shoreline is available for interpreting current studies using drogues. Additionally, the interpretation of sand transport directions in tracer sand experiments is facilitated.

Method

The shorelines are prism-rod surveyed using a Lietz Set 5 Total-Station infra-red laser theodolite with an on-board SDR-33 data recorder. Data was down-loaded and computer processed using Lietz's proprietary Sokkia Map software.

Products

Shorelines for various mapping days are shown on the same map for each of the three areas: Beach 6 (A:4); Lighthouse Beach (A:37); and Beach 10 (A:61).

C. Detailed Topographic Maps of the Beach and Nearshore

Rationale

Mapping of the surface was undertaken for three reasons:

1. To characterize the surface of the beach and the nearshore zone, especially in terms of the presence of bottom structures which may indicate sand movement. Such features as troughs and bars suggest that sand is intermittently stored in bars and then moved in troughs. The disposition or orientation of the bars can suggest whether the sand is moving offshore/onshore or perhaps along the shore.
2. To permit the visual comparison of the same area mapped on different days with patterns of changes potentially indicative of the dynamics of the system during the time interval represented.
3. To permit the construction of a second generation of profiles and maps using the topographic map or maps as the basis. Included in these second generation products are:
   (a) profiles along the transect lines using the Sokkia software Profiles;
   (b) contour maps of cut (erosion) and fill (accretion) which compare two topographic surfaces of the same area mapped on separate days using Sokkia computer software Volumes;
   (c) quantitative comparison of the topography of the same areas on different days yielding total volumes and total areas of cut as well as total volumes and total areas of fill using Sokkia Volumes software.

Method

Each of the transects in the detailed study areas was mapped from the front post across the exposed beach and shallow water areas to a depth of 2.5 m (8.2 ft). Mapping was performed by a prism-rod and Lietz Set-5 Total-Station infrared laser theodolite with an on-board SDR-33 data recorder. The deeper portions (up to 7 m [23 ft]) were surveyed by a boat equipped with a Lowrance X-16 precision depth recorder. A buoy was placed at the point of overlap and was mapped by both methods to correlate the two sets of data. Both sets of data were entered into the computer and processed with Lietz's proprietary Sokkia Map and Contours software.

Product

Eleven topographic maps of the nearshore zone and beaches were produced, four each for Beach 6 and Lighthouse Beach and three for Beach 10. All are presented at the scale of 1:4000 and contoured with a minor contour interval of 0.4 m (15.7 in, 1.3 ft) and a major contour interval of 2 m (6.6 ft). The maps are presented with their respective beaches in the Appendix: Beach 6 (A:5-8), Lighthouse Beach (A:38-41), and Beach 10 (A:62, A:62a, and A:63). The June map of the Beach 6 area does not include transects 19.5 and 20 due to ongoing nourishment in the area involving heavy equipment and rapidly changing landscape.

D. Volumetric Change Maps (Cut &Fill) Showing Contoured Areas of Erosion and Deposition

Rationale

Each map represents the comparison of two topographic maps of the identical area taken at two separate dates. Areas where the elevation of the surface of the second survey is higher than the elevation at the time of the first survey is an area of positive elevation change and is contoured in blue to indicate a gain in sediment volume (fill or accretion). Areas where the second survey indicated a loss in elevation of the surface are areas of negative elevation change and are contoured in red to indicate a loss of sediment volume (cut or erosion). Cut and fill maps are useful to delineate areas of erosion (cut areas) and areas of accretion (fill areas) produced during the period between the two topographic mapping days. Consequently, this is instrumental in the interpretation of movement of sediment. Areas of sediment loss are contoured in red on the maps to indicate the movement of sediment away from the area. Similarly, the blue-contoured areas experienced a gain in sediment showing that sediment moved into that area. The shape of the contoured areas of cut and fill permit the identification of bottom structures indicative of sediment transport. Elongate areas suggest trough forms and bar forms indicative of transport along shore; hummocky areas suggest interference of two or more wave and current regimes; and areas of relatively little change suggest areas of very little sediment transport. It is unclear if all of the sediment missing from the erosional areas has left the study area or, conversely, if all of the sediment added to the accretional areas came from outside the study area. A simple redistribution of sediment onshore or offshore within the study area could account for some of the patterns shown. Total volume changes for the study areas are dealt with in the Sand Transport Volumes computer product discussed below. The maps discussed here are used to derive the total volumes and total areas of both accretion and erosion from which a net mass budget can be determined.

Method

Two carefully surveyed topographic maps of the same area on different days provides all that is necessary for the generation of the cut and fill maps using Data Comparison in the Sokkia Map software (which also uses Contours and Volumes software). The areas compared are automatically limited to the areas which have been mapped on both days, thereby, eliminating any extra areas not mapped on one of the days.

Product

Eight Volumetric change (Cut & Fill) maps were generated: three comparing the four topographic maps of Beach 6; three comparing the four topographic maps of Lighthouse Beach; and two comparing the three topographic maps of Beach 10. Each map is presented at the scale of 1:4000 with a minor contour interval of 0.2 m (8 in) and a major contour interval of 1 m (39.37 in). The maps are presented in the Appendix and include Beach 6 (A:9-11); Lighthouse Beach (A:42-44); and Beach 10 (A:63a and A-64).

E. Comparison with Pre-Breakwater Nearshore and Beach Configurations

Rationale

Figures taken from Nummedal et al. (1984) show the pre-breakwater (dating from 1979) beach and nearshore configuration of bars in plan view and in depth profiles. Both views are critical for comparison with the current project's maps and profiles in order to determine any changes that may have occurred which may be attributable to the presence of the breakwaters.

Product

Three figures are included in the Appendix: Beach 6 (A:12); Lighthouse Beach (A:45); and Beach 10 (A:65).

F. Successive Profiles from the Exposed Beach to Seven Meters Depth for Each Mapping Day

Rationale

Generated at right-angles to the shore along each of the transects surveyed to create the topographic maps of the areas, the profiles are especially useful for identifying bar forms in the nearshore zone, particularly those which run parallel to the shoreline. With profiles generated along the same lines for each mapping day during the study period, the profiles also are ideal for showing any offshore or onshore migration of the bars over time. Although the shore-perpendicular disposition of the profile transects is ideal for delineating linear shore-parallel structures such as bars and troughs, areas of more chaotic, hummocky, topography were identified as well.

Method

The generation of topographic maps described above provides the basis for the generation of the profiles using the Lietz proprietary Sokkia software Profiles in conjunction with Map software. To permit better comparison of the changes in the distribution of bottom structures with time, a unique profile trace for the each of the either three or four mapping days is presented on a single plot for each of the transects (thus each transect profile sheet will have at least three different profile lines representing three different days).

Product

For each of the Beach 6 and the Lighthouse Beach areas, eleven separate sheets are presented with four separate profile traces representing the four separate mapping days (except for transects 19.5 and 20 at Beach 6 which have only three traces each due to the missed mapping day referred to above). The Beach 10 area is represented by eight separate sheets for the eight transects and each sheet has three profile traces, one for each mapping day. The profiles with the data from the appropriate beaches are presented in the Appendix and include Beach 6 profiles (A:13-23); Lighthouse Beach profiles (A:46-56); and Beach 10 profiles (A:66-73).

G. Current Studies Using Drogues

Rationale

Sand transport is primarily caused by currents in the nearshore zone. One way to understand sediment dispersal patterns with particular wave approach directions and energies is to release a floating drogue (see drogue sketch in A:24) which is moved predominantly by currents. The rate and direction of movement of the drogue may then be tracked.

Methods

Nearshore currents were analyzed by deploying a current drogue at various locations within the shallow nearshore zone and tracking the drogue's location each minute or two minutes (via two transects shooting and recording angles from two locations on the beach), thereby delineating the direction and velocity of the current propelling the drogue for the observed wave approach directions and wave height. With enough individual drogue runs in a variety of locations, a comprehensive picture of the circulation system for a given wave energy condition is generated. Detailed mapping of the bottom surface in the area of the drogue experiments is used to identify any features such as bars which may affect the current patterns. The location of the shoreline and the breakwaters is also mapped to allow consideration of their effects.

Products

Drogue experiments were performed at Beach 6 and at Lighthouse Beach. The results are presented with the appropriate beach in the Appendix and include Beach 6 drogue experiments (A:25-31, A:30a, A:30b, A:30c, A:31a and A:31b); Lighthouse Beach drogue experiments (A:57-59, A59a, and A-59b).

H. Sand Transport Studies Using Native Fluorescent Tracer Sand

Rationale

The determination of when and where sand is transported is the crux of the matter that has led to the various investigative activities described above. Nothing is as directly related to the sand transport as the tracking of actual sand grains as they move under the influences of the dynamic forces in the nearshore zone.

Method

Native sand collected from the study area is dyed with fluorescent dye and injected at a designated point within the nearshore zone prior to a time when wave energy is expected to increase to a moderate level (e.g. immediately prior to a moderate storm event). Immediately after the storm event, bottom sediment samples are obtained by a 2 inch PVC corer from underwater sampling grids that can be tied to the injection point(s). Samples are transferred to a plastic bag underwater and then brought back to the lab for drying and counting of the fluorescent sand content. The resulting distribution of fluorescent grain concentrations are contoured and used to calculate advection directions. During the experiments, bathymetric profiles and LEO data is also gathered to identify changes in the nearshore bathymetry and define the dynamics of the nearshore system during tracer dispersion.

Product

The two fluorescent sand tracer experiments were performed at Beach 6 on 30 August 1995 with one shallow injection and one deeper water injection. The results are in the Appendix with the Beach 6 data (A:32) and associated LEO data (A:33).

I. Littoral Environmental Observations (LEO)

Rationale

LEO data provides the basic framework for understanding the dynamic nature of the nearshore zone and beaches. Attention was focused on the way in which the breakwaters control various aspects of waves and currents. Analysis of this data provides part of the information necessary to generate models describing the dynamic character of the shorelines.

Method

Three locations were chosen at each of the study areas for recording the LEO data. Data was gathered for each day of significant wave energy and in conjunction with drogue and tracer experiments. Parameters measured include breaker height, breaker angle, breaker period, breaker type, longshore current velocity and direction, wind speed, and wind direction. Field sketches were made to depict the effect of the breakwaters on the various parameters.

Product

A key to the LEO tables is presented on A:31a. The bulk of the LEO data presented in the Appendix (A:74-79), with drogue-related LEOs (A:31b) and Tracer Experiment-related LEOs (A:33).

J. Sand Transport Volumes (based on computer analysis of sand volume changes between surfaces)

Rational

The topographic maps of each area at different times are the basis of comparisons which generate the Volumetric change maps, Cut and Fill. These contoured maps of accretion (fill) and erosion (cut) are beneficial in showing the areas where accretion or erosion has dominated during the period between the two mapping days. These maps are the basis for more strictly volumetric determinations which were calculated and are presented below in a separate section entitled Sand Transport Volume Comparisons. Total volumes of accretion over the entire map area are calculated and the total area of accretion is also reported. Similar figures are derived for erosion as well.

Method

Using the Volumetric change maps and the Lietz proprietary software Map, Contour, and Volumes, the calculation is made in the Volumes menu under Calculate void volume. Selecting the lowest (negative) elevation as Base level and 0.000 meters (of cut or fill) as Upper level, the calculation is made. The sediment budget for the period represented by the map is given.
The total accretion (fill) for the entire mapped area during the time period is reported (in cubic meters) as "Volume above upper level" and the area over which this accretion took place is reported as "Surface area above upper level." The total erosion (cut) is reported as the"Void volume" and the total area of erosion as " Surface area between base level and upper level." Comparison of the two volumes indicates if the budget is positive (accretionary) or negative (erosional). The total area of the map comparison is the sum of the two areas noted and is also reported as the "Surface area above base level." The same areas are not always compared throughout the course of the study so the total volumes reported for different time periods are not strictly comparable. It is valid to divide the volume in cubic meters by the appropriate area in square meters and derive a thickness in meters of either cut or fill that can be compared with similarly derived thicknesses for other time periods. We derive more directly comparable rates of accretion or erosion by taking into account the time period represented by the maps used to generate the data, and then recalculating the volumes and thicknesses at monthly (four-week) rates..

Product

The computer generated "Void volume" calculations are presented in the Appendix (A:82-88). The interpretation of the void volume data is presented in the summary table Sediment Transport Volumes - 1995 (A:8). For comparison, the Nummedal et al. (1984) pre-breakwater transport volume estimates are also presented (A:80).

Results

Introduction

The results of the sediment transport study are included in the Appendix Volume and will be treated sequentially in separate discussions of Beach 6, Lighthouse Beach, and Beach 10. A Sediment Transport Volumes section follows and the report ends with Recommendations.

Beach 6

The Beach 6 study area encompasses Breakwaters 20-24 (Appendix page A-1). It is in the largely erosional Neck Segment of Presque Isle (page A-2). Each transect is designated by either the number of the breakwater which it intersects or by a breakwater number and a suffix of 0.5 indicating that the transect occurs between two breakwaters (e.g., transect 19.5 is half-way between Breakwater 19 and Breakwater 20). Eleven transect profiles were mapped in the Beach 6 area from 19.5 to 24.5.

The aerial photograph of the Beach 6 area (page A-3) shows the nourishment area (also called Beach 5) with a truck on the beach adjacent to the groin opposite Breakwaters 19 , 20, and 21. The nourishment area is largely erosional as evidenced by the beach scarp. The beaches downdrift (up photo) are accretional and characterized by major widths of salients built behind Breakwaters 22-24. Lakeward in the nearshore zone of the photo there is only one poorly developed discontinuous trough indicated by an accumulation of dark organic matter. Prior to breakwater construction, Beach 6 and the entire Neck Segment was characterized by a well-developed system of arcuate inner bars, a trough which occupied the area approximately where the breakwaters are at present, and a substantial outer bar. This system is not visible in the photograph despite the fact that the waters were clear enough that it would have been apparent if still extant. Therefore, the inner bar, trough, outer bar system is no longer present at post-breakwater Beach 6.

Beach 6 shorelines for the mapping days 14 June, 24 July, 28 September and 12 October 1995 are shown in the Appendix on page A-4. The nourishment area shows variations attributable to initial erosion and subsequent build-up of a modest width of gently sloping beach. Downdrift of Beach 6, opposite Breakwaters 22-24, there is an increase in beach width during the entire period instead of the erosion which occurred during the same season prior to breakwall construction.

Topographic maps of the area for the June, July, September and October mapping days (A-5 to A-8) confirm the absence of the offshore bar and give some indication of what has happened to the nourishment material. As the presence of construction equipment in the photograph of 16 June indicates, beach nourishment was under way in the 19.5 and 20 transect area, and hence that portion of the study area was not included in the mapping of 14-15 June. The entire area was mapped on 24 July at which time a broad platform was present in the nearshore zone out to at least 500 m (1,650 ft) beyond the breakwaters. Subsequent mapping on the 28 September and 12 October 1995 also identified the platform. Mapping suggests growth of the platform in July with diminution by October, and that the platform growth may reflect movement of part of the nourishment material offshore to the platform early in the season with subsequent diminished supply of the nourishment material later in the season. The maintenance of a substantial beach width in the downdrift Beach

6 area is apparent in these maps as well, indicating that at least part of the nourishment sand is moving along the shore feeding those beaches.

The volume change maps show cut and fill and compare the surfaces represented by the sequence of any two topographic maps (A-9 to A-11). These maps show the region to be predominantly erosional. The mapping program contours the volume of accretion in areas of fill with blue contour lines and the volume of sediment that has been eroded or cut is contoured in red. Thus, areas contoured in blue are accretional and those contoured in red are erosional. The Beach 6 area is mostly contoured in red confirming that the area is predominantly erosional, especially for the period from June through September in the nearshore zone out 500 m plus. The beaches for the same period are somewhat accretional. The two week period in early October shows some accretion in the offshore area, but for the most part, the bulk of the area is erosional and computer calculation of the total sediment volume loss is presented in the Sand Transport Volumes section. An exception is seen just lakeward of Breakwaters 20 and 21 where a small shore-parallel bar can be seen contoured in blue.

Eleven profile sheets were generated, one for each transect, each of which has either three or four profile traces, one for each mapping day (A-13 to A-23). The pre-breakwater plan view of the Beach 6 area and pre-breakwater profile by Nummedal et al. (1984) are presented for comparison with those of the present study (A-12). Again, the profiles are notable for the lack of the outer bar, trough, and inner bar system shown so dramatically in the figure from pre-breakwater times. Note that the profiles in the Nummedal et al. publication used a 20x vertical exaggeration instead of the 10x exaggeration used in the present study. The pre-breakwater figure also shows the presence of the outer bar in plan view.

A current drogue (A- 24) was employed to delineate current pattern for various incident wave directions in the Beach 6 area. Drogue experiments were conducted on 12 June, 7 July, 17 July, 20 July, and 22 August 1995 (A-25 to A-30, 30a, 30b, 30c, 31). Two different wave approach directions were tested, one from the west and a second from the northeast. As might be expected, wave approach direction from the northeast resulted in the drogues being carried by currents back to the west, while approach directions from the west and northwest drove the currents, and thus the drogues, back to the east. Unlike similar drogue experiments that were conducted in pre-breakwater times, there was no effect of an inner bar, trough, outer bar system. Mapping of the drogue experiment area in great detail revealed only a very minor discontinuous bar present in the reentrant between the salients and only a few meters from the shoreline. The primary influence on the current patterns as shown by the drogues are the breakwaters themselves and the salient shorelines that have built up behind the breakwaters. Some areas midway between the breakwaters and their salients were found to have eddys that swirl and therefore do not carry the water (or sand) along the shore. Interestingly enough, there were no rip currents traced by drogues, perhaps putting to rest some fears that were expressed about the generation of life-threatening rip currents if the breakwaters were to be built.

Fluorescent native tracer sand experiments were run with both a shallow water injection point just east of transect 21.5 (red sand) and an injection point in deep water on transect line 21.5 (yellow sand) at the depth of the two adjacent breakwaters. The injection on the 30 August was followed by a moderately energetic wave producing storm. The shallow tracer sand was recovered from an orthogonal grid on 2 September and the deep sand was recovered by scuba diving a radial grid on

3 September 1995. LEOs were taken during the entire period (A-33) and show that the storm waves were from azimuth 270° or due west. The sand from the deep water injection moves in two primary directions. One was concentrated in the direction azimuth 60° to 90°, or on a course directly behind the west end of Breakwater 22, and the second direction was nearly due north carrying the sand just outside the west end of Breakwater 22. The shallow water injection was carried parallel to the shoreline of the salient, with the highest grain counts behind the west end of Breakwater 22. The sand movement from both injection points was to the area behind the adjacent breakwater in the direction opposite from the wave approach direction. Thus, a part of the sand from both sources goes to feed the salient building behind the breakwaters as a result of storms that drive waves in from the west. Additionally, the sand equidistant from shore and midway between breakwaters has a portion of its volume moved along the coast outside the breakwaters.

The total sand transport volume is analyzed by computer calculation of Volume Change Maps (Cut and Fill) and the precise volumes are reported in the Sand Transport Volumes section of the report. It should be mentioned here that the area which was largely erosional prior to breakwater construction remains in that state. The final analysis determined that the area lost nearly 182,000 cubic meters during the study period and nearly 70% of the ca. 500,000 m^2 of mapped area was erosional. Another way to put this is that a thickness of nearly 0.6 m (23.0 in) of sand was removed from the erosional part of the study area during the period.

Beach 6 Conclusions

Beach 6 is still predominantly erosional and will continue to need a substantial amount of nourishment sand each year. During the period of June-October, ca. 70% of the over 500,000 m^2 of the mapped nearshore zone and beach was erosional with a total thickness loss of 57.0 cm (22.5 in). The minimum volume of sand which moved through the area, or the total calculated loss was 181,873 m^3 during the four month period.

The nourishment sand emplaced in the Beach 5 area was largely lost during the course of the summer and fall, with part going offshore to form a broad platform and the remainder moving along shore feeding salient-widened beaches in the Beach 6 area.

The well-established inner bar, trough, outer bar system which characterized the neck of Presque Isle prior to breakwater construction (Nummedal et al. 1984) has been eliminated in the Beach 6 area. The removal of this sediment bypass mechanism coincides with the nourishment sand placed in the updrift Beach 5 area subsequently "feeding" the Beach 6 area downdrift rather than bypassing it.

Wave refraction around the breakwaters control the currents and most of the shallow water sand transport. Bottom features, such as bars, are limited in lateral extent to the areas between the salients and have only a minor effect on currents which are more strongly influenced by subaqueous portions of salients built behind the breakwaters.

Lighthouse Beach

The Lighthouse Beach area encompasses Breakwaters 43-47 (A-1). Eleven transects were mapped from 42.5 to 47.5. It is in the transitional Lighthouse Beaches Segment of Presque Isle where the dominantly erosional Neck Segment changes over to the dominantly accretional Gull

Point Segment (A-2). The trend of deposition and erosion along the Presque Isle beaches could be said to have a nodal point in the Lighthouse Beaches Segment. During the period from 19 June to 13 October 1995, erosion and deposition nearly balanced in the area with a loss of only -2.2 cm (-0.9 in.) in sediment thickness (see Sand Transport Volumes section).

Three aerial photographs taken on 16 June 1995 are included in the Appendix (A-34 to A-36) to illustrate various features of Lighthouse Beach. The updrift-of-jetty photo (A-34) shows that salients have built behind the breakwaters in the updrift area and have formed a broad accretionary beach there. In the nearshore zone just lakeward from the breakwaters is a lighter area in the photo that is a shore-parallel longshore bar bounded on both sides by darker areas that indicate troughs. The bar seems to end downdrift in front of the house at Breakwater 44. The next photo (A-35) shows Lighthouse Beach with broad salient-widened updrift beaches changing abruptly at the jetty to erosion-scarped beaches without salients downdrift. The lighter areas lakeward from the downdrift beaches (and at least twice the distance from shore as the breakwaters) are a complex of deep shore-parallel bars composed of large volumes of sand which has bypassed the erosional beaches. The photo of the same area looking updrift (A-36) illustrates two aspects of that area . First, there is a major inflection point in the trend of the Presque Isle shoreline at the Lighthouse Jetty which coincides with, and is most likely a significant factor in, a major change in the character of the beaches on either side. Salient-widened accretionary beaches occur on the updrift (west) side and erosional beaches occur on the downdrift (east) side. Second, the broad complex of shore-parallel bars and troughs are separated from the breakwaters immediately downdrift from the jetty by an area where no features are visible, and are cut periodically by shore-normal-trending swales. Additionally, the bar-trough system appears to be wrapping back to shore at the bottom of the photo near Breakwater 50, outside the study area.

The shorelines map (A-37) illustrates the accretional nature of the updrift beaches culminating in the connection of the beach to Breakwater 44 as a tombolo on the 13 October shoreline. The downdrift beaches have remained relatively constant in width in spite of substantial nourishment concentrated there. It is significant that the downdrift beaches did not grow in response to the nourishment there. The question arises, what happened to the nourishment sand?

The topographic maps generated by surveys on 20 June (A-38), 25 July (A-39), 24 September (A-40), and 13 October 1995 (A-41) dramatically illustrate the bar and trough complex in the nearshore zone. The features migrate offshore and onshore during the course of the season but remain shore-parallel with a progressively greater shore-normal component toward the east or downdrift direction. The aerial photography and the maps match, reassuring us of the accuracy of the mapping. The lack of features opposite the erosional beaches and for some distance lakeward of the Breakwaters (45 to 47) indicates that the dynamics of sediment transport that formed the complex are apparently absent in this area. In other words, sediment is apparently bypassing the erosional beaches. Another apparent trend is that the longshore component seems to become increasingly dominant later in the season (on the 24 September and 13 October maps) suggesting that whatever causes the shore-normal interruption of the longshore pattern becomes less effective as Autumn approaches. In terms of the nearshore, there seems to be no accretion in the subaqueous area adjacent to the downdriftbeaches for the entire period. In contrast, the updrift beaches show growth as reflected by both the shoreline changes and the increase in elevation behind the breakwaters.

The Volume Change maps compare successive topographic maps (A-42 to A-44) showing areas of accretion or fill (contoured in blue) and areas of erosion or cut (contoured in red). The subequal areas of blue contours and red contours confirm the balance between erosion and accretion in the Lighthouse Beach area. The computer analysis of these maps for total volumes and their balance (the mass balance) confirms a rough balance volumetrically as well (see Sediment Transport Volume section). Additionally, the areas of erosion and areas of accretion are distributed in a shore-parallel manner and correspond to troughs and bars, respectively. A very significant aspect is that a wide area lakeward from the breakwaters (45, 46 and 47) enclosing the erosional beaches shows essentially no change from 19 June to 13 October 1995, with less than 0.4 m (16.0 in) of sediment thickness added or removed. This area is apparently not one where sediment is being transported (as reflected by the absence of significant cut or fill, which would occur if a bar were to move through the area). One possible conclusion is that the nourishment applied to the beaches is not moving to the bar complex through this intervening area.

Profiles generated for 42.5 to 47.5 transects and for each of the four mapping days (A-66 to A-73) illustrate dramatically the existence of the shore-parallel bars and troughs in the deep nearshore zone and show that the complex is adjacent to the breakwaters in the updrift beaches area and separated from the breakwaters in the downdrift area by a relatively flat area of some 200 meters (660 feet). The profiles, of course, do not show the shore-normal components of the bottom topography. Comparison with the beach and nearshore configuration and depth profiles (A-45) of Nummedal et al. (1984) shows that the region prior to breakwater construction was essentially identical to that mapped in this study in 1995. On the Nummedal figure, profile number 61 is just to the east of the Lighthouse Jetty.

Drogue experiments were conducted between 43.5 and 44.5 on 11 July, 18 July, and 19 July with wave approach direction from about 300° (within 15° of a northwest approach direction). Not surprisingly, the currents are to the east along the shore and are influenced by the breakwaters and the salient shorelines. Very few drogues, and therefore very little current, passed behind Breakwater 44, indicating that the removal of a tombolo there would not result in the stimulation of a current behind the breakwater. Another dramatic result is the discovery that the area from 44 to 44.5 and beyond, in other words from Breakwater 44 to the Lighthouse Jetty, shows no through-flowing currents from Breakwater 44 around the Lighthouse Jetty. In fact, the return of drogues to their area of release indicates currents that are circular even with a westward source of wave energy. This suggests that transport of sediment from the updrift beaches around the Lighthouse Jetty to the downdrift beaches is impossible with the wave approach direction tested.

Littoral Environmental Observations (LEO) taken in the downdrift beaches area show that the waves from the west do not break until they are immediately adjacent to the shore and a significant shore-parallel current is generated to the east. Apparently the breakwaters are not attenuating wave energy in this location for the most energetic wave regimes. The suggestion is that nourishment material placed on these beaches is carried downdrift in a narrow zone immediately adjacent to the shoreline. There is no indication that sediment is moved in an offshore direction with the possibility of return during low energy wave regimes. Once the sediment has been removed it apparently does not return by natural processes.

Lighthouse Beach Conclusions

Taken as a whole, the area is volumetrically nearly balanced with a total loss over the June to October period of only 2.2 cm (0.9 in) in thickness over an erosional area of ca. 51% of the over 580,000 m^2 of the mapped nearshore zone and beach. Losses through September were offset by gains thereafter (through 13 October 1995.)

The area updrift (west) of the Lighthouse Jetty is characterized by salient-widened accretionary beaches and is thus very different from the erosion-scarped beaches of the area downdrift (east). Additionally, it is apparent that sediment from the updrift area does not in any volumetrically meaningful way reach the downdrift beaches.

A system of at least two shore-parallel troughs and two shore-parallel bars is present in the nearshore zone beyond the breakwaters immediately adjacent to the updrift area and separated from the downdrift beaches by a wide featureless area where little sand movement is occurring. Since the bars and troughs indicate areas of sediment transport, the distribution of these features indicates sediment bypass of the downdrift Lighthouse beaches.

Tombolo formation in the updrift beach area does not cause the starvation of the downdrift beaches, and therefore tombolo removal does not result in increased sand reaching the downdrift beaches.

Changes in the shoreline trend with an inflection point at the Lighthouse Jetty seem to have caused the sediment to bypass the downdrift beaches, and there is therefore no management solution to the problem.

Nourishment sand placed on the downdrift beaches moves almost entirely along the shore in a narrow band carried by currents driven by waves that slip in unmodified in energy by the adjacent breakwaters (45 through 47).

Beach 10

The Beach 10 area encompasses Breakwaters 57, 58 and prototype Breakwaters 1, 2, znd 3 (pg. A-1). It is located on the western,updrift, end of the largely accretional Gull Point Segment of Presque Isle (A-2). All of the data accrued to date indicate that this study area remains overwhelmingly accretional with a substantial positive net mass sand budget. During the August - September 1995 portion of the study period 42 cm.(17 in.) of sediment accumulated ref;ecting this overall predominance of accretion over erosion (see Sand Transport Volumes Section).

As the aerial photograph (A-60) of Beach 10 indicates, the offshore area is a broad, hummocky, subaqueous plain composed primarily of accretionary sand features. This complex of features is fed and shaped by a reduced, but still dominant southwesterly wave regime and modified by full exposure to northwesterly waves produced by cyclonic storms which regularly pass by to the north of Beach 10.

All data collected during the 1995 study confirms the accretionary character of Beach 10. The shorelines map (A-61) indicates the formation of salients behind Breakwaters 57 and 58 during the course of the study culminating in th eformatin of a tombolo reattaching itself to Breakwater 58 in November of 1995. The shorelines map indicates that the formation of the tombolo did not induce any significant erosion down drift.

Topographic maps (A-61a, A-62, and A-63) confirm that there is no major shore-parallel component to the observed bottom structures. Although there are clearly areas of major and minor buildup or accumulation, these , as noted above, are hummocky not linear. Clearly the general absence of linear features shows that sand transport in this area is not occurring in a unidirectional fashion via troughs and bars but rather is subject to redistribution episodically in various directions.

The volumetric change maps of cut and fill (A-63a to 65) again confirm the accretionary character pf Beach 10 but do show at least one trough component behin Breakwaters 57 and 58. More typically, these maps substantiate the existence of a variety of apparently random high and low areas across the offshore plain in the nearshore zone. The Profiles generated by this study (A-66 to A73) confirm that the topography is essential the same in variety and character as that(A-65) observed by Nummedal et. al. (1984).

Littoral Environmental Observations (LEOs) of Beach 10 (A-74 to A-79) were taken at transects 57.5, 58 (directly behind Breakwater 58), and 58.5. All LEOs show wave refraction due to the overall spit configuration with wave approach directions ca. 10 ot 30 degrees more northeasterly than in the Lighthouse and Beach 6 areas. Because of this refraction the dominance of west to east waves and currents is not as great in the Beach 10 area as at Beach 6 on the Neck Segment or in the transitional Lighhouse Beach area.

Beach 10 Conclusions

The Beach 10 area is dominantly accretional needing little management activity aside from dealing with tombolo formation. It is possible to determine exactly how much sand is added to this part of the system as demonstrated in the Sadn Transport Volumes Section. Perhaps a yearly monitoring of this mass balance would be a useful thing for those concerned with the effects of breakwaters on the growth of Gull Point

The nearshore zone off Beach 10 is a complex of hummocky topography resulting large volumes of sand being carried in and shaped by waves and currents from the dominant SW approach direction and the subsequent modification of the bottom structures by NE source winds and waves that follow as each cyclonic storm system passes by to the north of the area. The orientation of the beaches in this part of the spit make them particularly susceptible to NE wave regimes.

Sediment Transport Volumes - 1995

Of all the products generated by this project, none is more directly linked to the role of breakwaters and the maintenance of the nearshore zone and adjacent Presque Isle Beaches than sediment transport volumes. In effect, the calculation of the net gain or loss at each of the studied loci is critical to ascertaining the relative effect of breakwaters at each area. While net gain or accretion does not automatically signal successful breakwater function any more than net loss or erosion marks breakwater failure, the simple fact of the matter is that the determination of the net mass sediment balance is critical to those who will judge the function and cost effectiveness of the breakwaters at least partially on that basis.

As noted previously (see Introduction) and as reiterated and expanded here, the net mass budget data presented in the Sediment Transport Volumes table (A-81) constitute a third generation data set. This data has been calculated from Volumetric Change Maps of cut and fill which were generated by comparison of two Topographic Map surfaces of the same area on different surveying days using Lietz proprietary software Map and Volumes.

The section of this report entitled, "Computer Analysis - Sediment Volume Changes Between Surfaces" (A-82 to A-88a and A88b) provides the computer output used to create the table Sediment Transport Volumes - 1995 (A-81). The "void volume" is equal to the volume of erosion (cut) between the two dates compared on the volumetric change map. The "surface area between base level and upper level" is the total area erosional area. The accrectional volume (fill) is reported as "volume above upper level" and the total area of accretion as "surface area above upper level".

The Sediment Transport Volumes - 1995 table (A-81) presents the data from the section, Computer Analysis - Sediment Volume Changes Between Surfaces and additional information derived directly from that data. Highlighted in the table are the mass balance totals of the volume changes for Beach 6, Lighthouse Beach, and Beach 10 during the entire study. Because the volume change figures represent different size mapping areas for each beach and are hence not directly comparable, the change in thicknesses which *are* comparable, are also presented. The thickness values are obtained by dividing each total volume change figure by the appropriate area within which the volume change occurred. For a negative volume change total, the average area of erosion is used; for a positive volume change total, the average area of accretion is used. The mass balance number reported under Balance for the time between two compared mapping days is simply the sum of the volume of accretion (a positive number) and the volume of erosion (a negative number). A positive balance is therefore indicative of net accretion and a negative balance, of net erosion. The balance is also equal to the minimum transport volume of sediment which has moved through the study area (assuming only the excess material moved either into or out of the area). The maximum transport volume is therefore the sum of the absolute values of accretion and erosion based on the assumption that the entire volume of erosion has left the study area and the entire volume of accretion has come into the area from outside.

Because the elapsed time between the mapping days is variable, the balances are not directly comparable. To provide more directly comparable figures, a monthly rate was calculated and presented in the last column which is a recalibration of the balance figures to reflect a monthly (i.e. 4 week) basis. For example, to calculate a monthly rate, the balance value for a 7 week period from 6/6 to 7/26/95 is recalibrated by multiplying by 4/7.

From a cursory inspection of the yearly balance figures in Table A-81 (which follows the practice of Pope and Gorecki 1982 and Nummedal et al. 1984), it is apparent that Beach 6 is dominantly erosional with a loss of -181,873 m^3 over about 70% of the mapped area of 477,077 m^2 The resultant thickness loss in the erosional area is -57cm or -22.5 in. The same analysis for Lighthouse Beach for the period June until mid-October indicates a loss of only -938 m^3 instead of -181,873 m^3. In general, a relative balance between volumes of erosion and accretion is indicated with the area of erosion at about 50% of the mapped area of 601,346 m^2 and a thickness loss at Lighthouse Beach of -2.2 cm or -0.9 inches. The Beach 10 area is slightly accretional over the entire study period with a gain of 51,563 m^3 over about 50 % of the area of 443,531m^2 for a thickness gain of 20.9 cm or 8.2 in. In sum, from a yearly perspective, Beach 6 on the Neck Segment of Presque Isle is dominantly erosional, as has been established since 1877. The Lighthouse Beach area which is supposed to be in the transitional zone between erosion and accretion is in fact almost balanced in accretion and erosion, again based on the entire year. Beach 10, which is known to be predominantly accretional, is, in this analysis for the summer of 1995, only slightly accretional with a modest increase of 52,000 m^3. This is slightly in excess of the Nummedal et al. (1984) estimate of a 45,000 m^3 gain. However, most of the other figures presented in Table A-81 are at least 10 times greater than Nummedal et. al (1984) estimates. On this order of magnitude, the accretion at Beach 10 should be at least on a par with a loss of ca. -182,000 m^3 at Beach 6, on the Neck Segment of Presque Isle. This conclusion is based on the Nummedal et al. (1984) cited net loss in the Neck area which is on the order of -44,000 m^3 and broadly equivalent gains in the Gull Point area, on the order of 45,000 m^3. If the situation at present is balanced, a gain of 182,000 m^3 should have occurred in the Beach 10 area (instead of 52,000 m^3).

Repeated mapping followed by volume calculations *throughout* the year provides data not available or observable in yearly calculations. If volume calculations are made seasonally, a pattern of significant erosion during early summer through early autumn followed by much decreased erosion in the late autumn is revealed for Beach 6. Specifically, Beach 6 experienced a monthly loss of -52,090 m^3 and a thickness loss of -16.2 cm (6.4 in) for the mid-June through late July period. The erosional pattern continued, and in fact, accelerated, during the subsequent period of late July through early September, with a monthly loss of -62,459 m^3 and a -14.5 cm (-5.7 in) thickness loss. A dramatic decline in erosion occurred from late September through mid-October, with a monthly loss of only -7,688 m^3 and a thickness loss of -3.2 cm (-1.2 in).

Seasonal volume calculations for Lighthouse Beach reveal considerable erosion in early summer, diminished erosion by late summer-early fall, and dramatic offsetting accretion in the late fall. Lighthouse Beach experienced major erosion during mid-June through late July, with a loss of -37,934 m^3 and a thickness loss of -10.4 cm (-4.1 in). For the period of August through September, the rate of erosion declined, with a loss of -10,966 m^3 and a thickness loss of -3.8 cm (-1.5 in). During late September through mid-October, the erosional trend reversed, and Lighthouse Beach experienced an actual gain of 104,881 m^3 and a thickness gain of 35.0 cm (13.8 in).

Analysis of sediment transport volumes on a seasonal rather than yearly basis facilitates a more accurate and dynamic definition of a nodal point for the Presque Isle beaches. The nodal point is defined as that locus where the net balance of sediment transport changes from erosional to depositional. If considered on an annual basis, the 1995 nodal point would be located very close to Lighthouse Beach, based upon a negative or erosional balance for Beach 6, a positive or accretional balance for Beach 10, and a slightly erosional balance for Lighthouse Beach. When sediment transport volume is analyzed seasonally, however, the location of the nodal point migrates. In the early summer (mid-June through late July), all three study areas have erosional balances and the nodal point is on the Gull Point side of Beach 10. During the mid-summer through early fall (late July through late September), Lighthouse Beach has an erosional balance while Beach 10 has a depositional balance, and hence the nodal point during this period shifts to a locus between these two beaches. In the late fall (late September through mid-October), Beach 6 remains erosional while Lighthouse Beach shifts to a positive, depositional balance. The nodal point therefore migrates westward during this period to a locus between Beach 6 and Lighthouse Beach.

Recommendations

Beach 6 Area (Breakwaters 20 - 24)

The model suggests a continuation of nourishment in the updrift Beach 5 portion of Presque Isle, opposite breakwaters 20 and 21. Most of the sand placed there will be removed within the year, with part moving offshore and a significant volume also feeding the downdrift Beach 6 area in a manner that did not occur prior to breakwater construction. The optimum yearly replenishment volume is not obvious from present calculations, but considering the measured total loss of more than 180,000 m^3 from the entire erosional area during the four monthsof 1995 for thickness loss of more than -0.5 m (more than -1.5 ft) in thickness, a substantial amount will clearly be necessary. Enough nourishment to protect the Beach 5 area during the summer and fall will apparently also be adequate to feed the downdrift area.

Lighthouse Beach Area (Breakwaters 43 - 47)

Nourishment of the erosional beaches downdrift from the jetty will continue to be necessary. Although waves and currents will not reshape the nourishment material into a broad, sloping beach, an amount of sand adequate to protect the land behind the beach should be emplaced and the beach should be shaped for recreational use rather than promoting the formation of a vertical scarp by building a flat-topped plateau.

Ignore the formation of tombolos updrift unless they constitute a cost-effective source of nourishment sand. Tombolo formation apparently has no adverse effects on the beaches downdrift and the removal of tombolos does not appear to promote sediment transport to the downdrift beaches.

Beach 10 Area (Breakwaters 57, 58, Prototype Breakwaters 1, 2, and 3)

A seasonal monitoring of this mass balance would be useful because of the heretofore undocumented early summer erosion. It is possible to determine exactly how much sand is added or removed to this part of the system as demonstrated in the Sediment Transport Volumes section. Any increase in sediment loss relative to the late season sediment gain for this most updrift portion of the Gull Point Segment might have severe repercussions on the growth of Gull Point proper.

No action is recommended for the Beach 10 area beyond monitoring. Any significant changes that occur in the area will result from previous nourishment updrift. No immediate management activity will have any significant impact on the system. Periodic analysis of the volumetric change of the nearshore zone and beach would give a sufficient indication of the progress of the system.

Acknowledgements

The 1995 Presque Isle sediment transport study was conducted by the Geology Division of the Mercyhurst Archaeological Institute under the supervision of M. R. Buyce, Principal Investigator. Field observations, mapping and measurements were supervised by M. R. Buyce and K. Taylor with field assistants R. Kowalkowski, N. Croasmun, University of Akron, W. Pelletier and S. Neckers, Mercyhurst College. Compilation and interpretation of data was conducted by M. R. Buyce. K. Taylor assembled the Littoral Environmental Observations and C. Carter, University of Akron, supervised Master's candidate N. Croasmun in the counting and analysis of the sand tracer studies. Assistance in computation and processing of data was provided by K. de Dufour, M. Shiels and S. Whitlach, Mercyhurst College, while the report production phase involved W. Pelletier, C. Pelletier, K. Presler and D. M. Franz in addition to K. de Dufour. Editorial assistance was afforded by J. E. Thomas, A. Quinn, and J. M. Adovasio, Mercyhurst Archaeological Institute.

The Authors wish to gratefully recognise the cooperation and assistance of H. Leslie and D. Rutkowski, Presque Isle State Park, R. Crawford, Pennsylvania Department of Conservation and Natural Resources surveyor, and M. Mohr, U. S. Army Corps of Engineers, Buffalo District.

References Cited

Nummedal, D., D. L. Sonnenfeld, and K. Taylor
1984 Sediment Transport and Morphology at the Surf Zone of Presque Isle, Lake Erie, Pennsylvania. In Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments, edited by B. Greenwood and R. A. Davis Jr. *Geology* 60:99-122.

Pope, J., and R. J. Gorecki
1982 Geologic and Engineering History of Presque Isle Peninsula, PA. In *Geology of the Northern Appalachian Basin, Western New York*, edited by E. J. Buehler and P. E. Calkin, pp. 183-216. Guidebook, New York State Geological Association 54th Annual Meeting, Amherst, New York.